

PREFERENTIAL FLOW INFLUENCES ON DRAINAGE OF SHALLOW SLOPING SOILS

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ABSTRACT

The dramatic effect of flow through macropores and hardpan fissures on artificial drainage in shallow sloping soils is demonstrated. Implications of these preferential flow mechanisms on drainage design and water management are discussed. In designing drainage systems on these types of soils, more emphasis should be given to the characteristics of the hardpan.

INTRODUCTION

A great deal of effort has been expended in recent years exploring the preferential movement of water through heterogenous soils. Preferential flow as caused by macropores and wetting front instabilities has been the focus of extensive experimental and theoretical research, as thoroughly reviewed elsewhere (Bouma, 1981; Beven and Germann, 1982; Nielsen et al., 1986). Thus far relatively few investigations into the management implications of this work have been reported (Ahuja et al., 1984; Smith et al., 1985; Wang et al., 1986; Moore et al., 1986).

This paper is a first attempt to incorporate our observations of macropore flow through shallow soils (i.e. soils with a hardpan at shallow depth) in a theoretical framework which can be used to model water flow to tile drains. Design and management of drainage systems is of particular concern in these soils as the thin topsoil is prone to both trafficability problems in the spring and drought stress in the summer. Drainage can be a solution for one problem yet exacerbate the other. In this paper we describe the physical flow processes that have been observed to be significant, and their probable impact on drainage systems as traditionally designed. In a subsequent paper we will formulate the mathematics which can be used to model this system, and explore some alternative drainage design and management systems.

The flow mechanisms discussed have been identified in field research during the last five years on shallow soils in Upstate New York. Our findings are consistent with the results of several other studies in the United States. Bornstein and coworkers carried out an interception drainage research project initiated in 1958 at East Franklin, Vermont, to develop and evaluate drainage practices (Bornstein, 1964; Bornstein et al., 1965; Bornstein et al., 1965; Bornstein et al., 1967; Bornstein and Benoit, 1967; Benoit and Bornstein, 1972). In Ohio investigations of tile drains (and

shallow soils) have been reported by Fausey, Schwab and coworkers. (Fausey, 1981; Schwab et al., 1963). Walter, et al. (1977) studied the underdrain response in fragipan soil in the Finger Lakes region in Upstate New York. In each of these studies preferential flow could well explain observed tile flow patterns which are inconsistent with homogeneous flow theory. The actual pathways of preferential flow to tile drains have been clearly identified in Missouri where the process was studied by Kramer and Burwell (1978). In the Netherlands, Bouma et al. (1981) found that the flow in a heavy clay soil towards the tile line occurred almost exclusively along macropores. In addition to this drainage oriented research there have been several studies dealing with the hydrology of undrained shallow soils. These are reviewed extensively by Richard (1987), Parlange (1987) and Aburime (1986).

The hardpan which underlies shallow soils has a critical influence on the hydrology of the system. It is usually assumed in mathematical analysis that the hardpan is impermeable and uniform (Nieber and Walter, 1981; Sloan and Moore, 1983; Stagnitti et al., 1986). Though relatively easy to model, a completely uniform layer does not typically occur in nature. Plant and tree roots may extend to considerable depth; worm-holes may penetrate the subsurface pan; and, as is often the case with a fragipan horizon, a network of vertical cracks may exist in the dense subsurface layer.

The fragipan is one type of subsurface horizon of widespread importance. It has been observed and classified throughout Western Europe, Canada, New Zealand, and the northern United States (Smalley and Davin, 1982). Fragipans have been found throughout these regions on both flat ground and on hillslopes as great as 30-40%. Typically the fragipan is found to be a loamy clay horizon with very low organic matter content and a greater bulk density than overlying layers. When dry the pan appears cemented and when moist it exhibits moderate brittleness. Some fragipans are composed of polygonal networks of interconnected vertical fissures (Fig. 1) (Van Vliet and Langohr, 1981). The cracks may extend at narrow width (<1 cm) to depths of one or two meters. At the pan surface the crack openings have been observed to be 13 cm wide (Carlisle, 1954).

MATERIALS AND METHODS

Experiments at three sites are discussed. The first is at Turkey Hill near Ithaca, where all the water that fell on the plot was collected and accounted for in either a tile line at 1 m depth or an overland collection system. The second experimental site was at Mount Pleasant, also near Ithaca, where most of the water flowed through the cracks in the hardpan and only a minimal amount was collected in a shallow tile line, located on the surface of the hardpan. There was no overland flow at the Mount Pleasant site. At both sites the depth of the impermeable layer was approximately 40 cm. Differences between the flow regimes were attributed to differences in characteristics of the hardpan at the two sites. At Turkey Hill the hardpan was extremely tight while at Mount Pleasant the hardpan had a blocky structure with fingers of highly permeable soil between the structural units. These highly permeable pathways permitted preferential flow through the hardpan both vertically and laterally downslope.

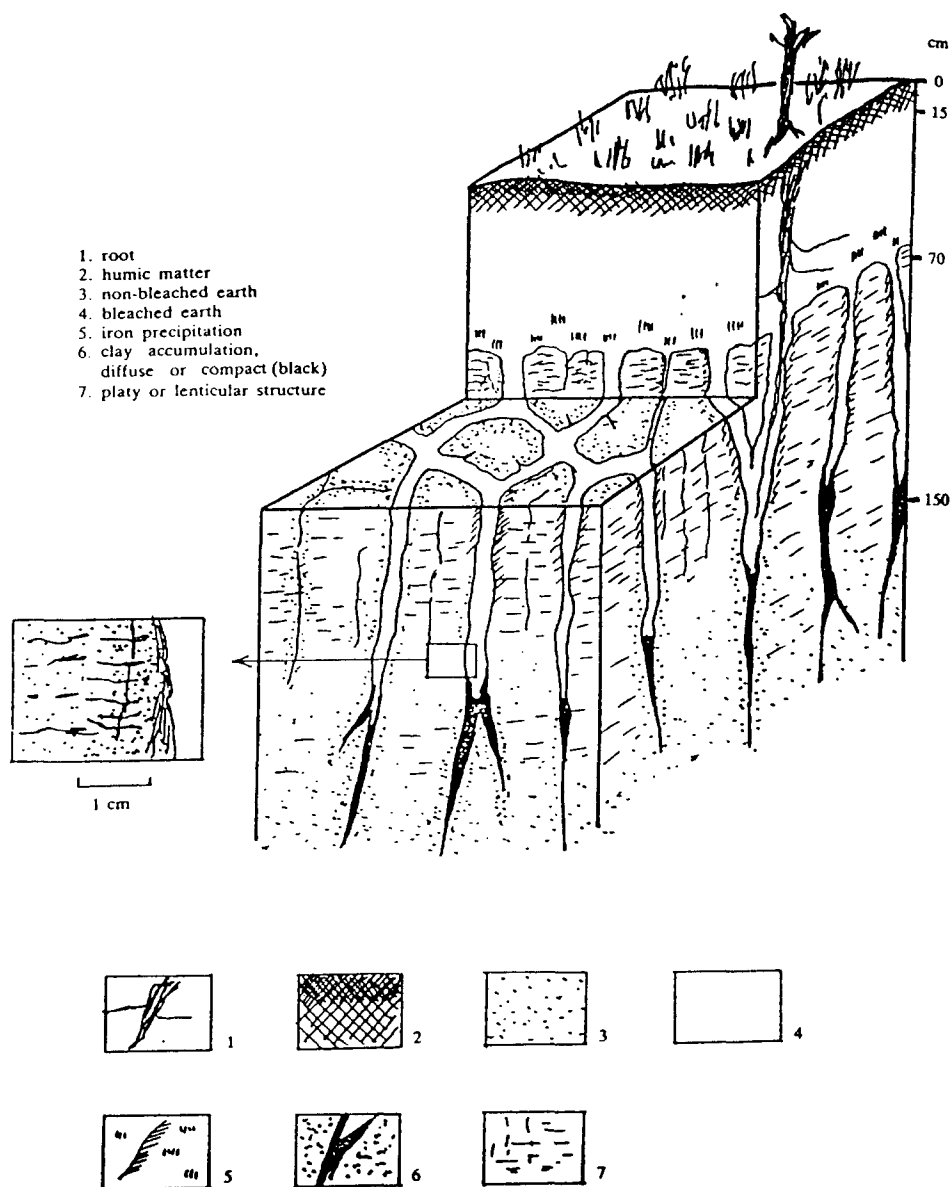


Fig. 1. Schematic representation of a fragipan (Van Vliet and Langohr 1981; Smaley and Davin, 1982).

The third site was at Willsboro in Northern New York near Lake Champlain and contained three distinct soil layers. The top 30 cm was high in organic matter and fairly permeable with a saturated conductivity in the order of 5 cm/day (Bro, 1964). The second layer from 30-60 cm was a tight clay layer. Worm and root holes penetrated the layer every few centimeters. Beneath this clay layer at 80 cm depth there was a more permeable subsoil in which the drains were located. Each of the sites is discussed in more detail below.

Turkey hill: Field tests at the Turkey Hill research site were performed from December 1978 until March 1981. The study included three experiments each replicated twice. The treatments consisted of: 1) uniformly distributed surface application of chloride and nitrate at a rate of 50 kg/ha to saturated soil; and 2) incorporation of the chemicals in a band 50 cm wide and 30 cm deep at 35 and 70 meter upslope. The soil is a Langford Channery silt loam. The plot is 23 m wide and 109 m long with an area of 0.25 ha. The surface slope is a uniform 8%. A plastic barrier in the soil and a berm prevents foreign water entering the plot. A timothy hay grass mixture had been established in 1974 and a good stand is present. At the lower end of the plot both the volume and quality of subsurface and surface runoff are measured. Volume measurements are made with a V-notch weir while water samples were taken at intervals ranging from 5 minutes (just after application) to 1 hour at the end of the experiment. A sprinkler irrigation system was used for applying artificial rainfall. The precipitation rate for the first three experiments was 0.5 cm/hr and for the remaining experiments 0.2 cm/hr.

Mount Pleasant: A 10 cm tile line was installed across a 12% slope approximately 2 cm into the hardpan in May of 1985. A heavy vinyl plastic sheet was fitted from the bottom of the tile line and stretched behind up to the soil surface, along the entire drain length. A small manhole at the outlet of the tile provided a position for flow measurement. A network of 26 tensiometer stations was placed throughout the field. Each station consisted of 3 tensiometers; 15 cm, 30 cm and 45 cm below the soil surface. Three to five tensiometers stations were placed in six rows (parallel to the tile line) at distances 5 m apart uphill. A small irrigation system was used to simulate precipitation. The average application rate was approximately 0.5 cm/hr with a duration of 6 to 8 hours. The tensiometers were read at least once a day as well as just prior to and just after each irrigation event. A total of 15 separate irrigation events were studied during the summer of 1985.

Willsboro: A tile drainage system was installed in the field during the fall of 1984. Four lateral tile lines were installed at a 20 m spacing each of which passes through an access chamber for monitoring prior to entering a collector drain at the east end of the field. Lateral tile depth averages approximately 80 cm, with the collector drain at an average depth of 1.8 m. Perimeter drains at approximately 1.5 m depth are located on the north, west, and south borders of the field to complete the isolation of the field from subsurface flows. The overall slope of the field averages 2 to 3% from south to north. The soil is mapped as Rhinebeck Variant fine sandy loam, and contains a dense clay B horizon underlain by a more permeable gravelly fine sandy loam. Prior to the experiments the field had not been plowed for several decades, nor had any herbicides or fertilizer been applied. The only regular farm traffic over the field was for mowing and baling of hay.

Centered on each lateral tile line are four experimental plots, designated A, B, C and D with areas of approximately 0.257, 0.251, 0.245 and 0.221 hectares respectively. Plots A and C were used during the first year's experiments and plots B and D during the second year. In the fall each year, calcium chloride dihydrate was applied in flake form to the soil surface in bands parallel to the drain tile at a distance between 2 and 5.5 m up gradient. During the first year artificial rainfall was used but the second year, on which we report here, depended entirely on natural precipitation to move the tracer through the soils. During the second year a total of 80 kg of chloride were applied to each plot. Each drain tile's flow rates were measured at 30 minute intervals using a 30 degree V-notch weir with a stilling well. Tile effluent was sampled for chloride concentration using an automatic sampler. Quantity and quality of the tile outflow was measured for a year afterwards. The mass balance performed at the end of the experiment could account for all of the chloride applied.

HOMOGENEOUS VERSUS NONHOMOGENEOUS MOVEMENT

Traditional theories and models describing water and solute flow assume that flow occurs at equal rates through the soil matrix. While this seems to be largely true in laboratory columns of homogeneous soils, a heterogeneous soil with areas of varying permeability, structured clay subsoil, or large biologically created pores can behave in a very different manner.

An assessment of the magnitude of macropore influences on solute transport can be attained by comparing the observed solute loss with the predictions of an homogeneous model such as Kirkham's (1958) steady state analytical solution of the pressure potential and streamline distribution in the saturated soil of a tile drained system. Jury (1975a, b) used this model to determine travel time of solutes. In the Willsboro experiment the chloride was applied at the surface in a band beginning 2 m from the tile line. This distance will be used to define the streamtube of interest. For this proximity to the tile line the solution is not very sensitive to the impermeable layer depth, so the assumption that it is at 2 m depth should be adequate. If we assume in addition that the highest observed flow rate (0.5 cm/day) equalled the steady state flow rate, we find, based on Jury (1975a, b), a travel time of 8 days for the saturated layer and 16 days through the unsaturated zone (Richard, 1987).

The experimental results for the solute outflow at Willsboro show a travel time of less than one day, as seen in Fig. 2. Chloride was applied at the surface of the soil in the afternoon of October 12th, Julian day 285. Rainfall began the following morning at approximately 4:30 and the chloride concentration started to rise at 9:00 and peaked that noon at 245 mg/l. This pattern was repeated October 15th, when the chloride concentration rose dramatically just 3 hours after the precipitation began and peaked after another 3 hours.

The Turkey hill plots showed the same trend as the Willsboro plots. Chloride incorporated approximately 70 m upslope from the collection point travelled that distance within a few hours (Fig. 3). These much shorter than expected travel times are strong evidence that the macropores form an important conductor in water and solute transport.

Dye studies at Willsboro also demonstrated the importance of macropore preferential flow on the hydrology of shallow soils. In these soils wormholes and root channels are the most important pathways transporting water

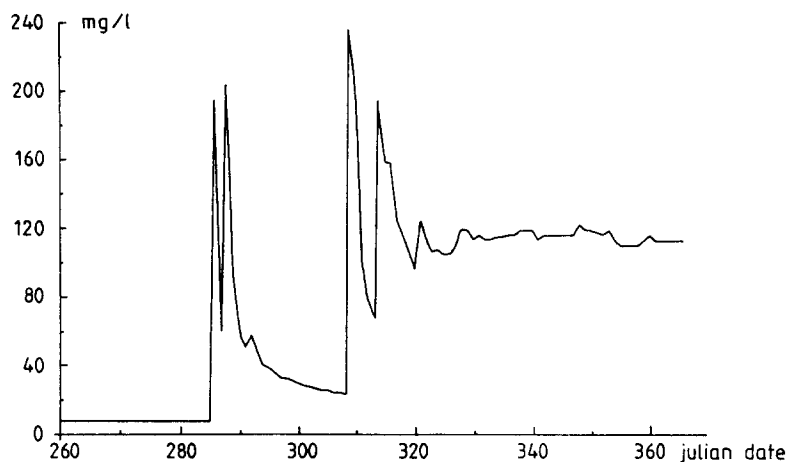


Fig. 2. Tile Chloride concentration for plot D at Willsboro. Chloride was applied at day 285.

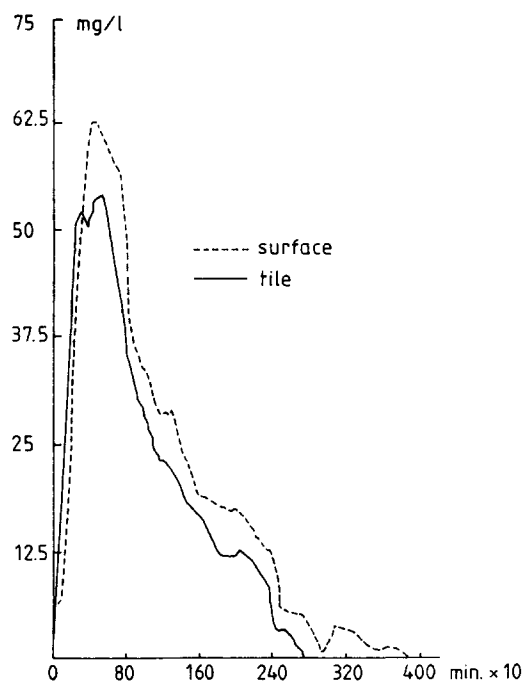


Fig. 3. Chloride concentration in the tile and surface flows for Turkey Hill as a function of time after band application at 70 m upslope.

and solutes through the otherwise impermeable clay layer. These pathways were not related to cracks but were distributed more or less at random and were oriented almost vertically up and down. There was another interesting observation that affirmed the extent of the preferential flow. Prior to the second dye experiment a 3 by 5 m area of the plot was irrigated with 20 cm of water over a period of 5 hours. The groundwater level in the immediate area remained well below the tile line. Despite this, water started flowing out of the tile lines. This was clearly an impossibility under the homogeneous soil theory, but quite possible when the soil has a direct pathway from the surface layer to the tile line.

A dye study at Mount Pleasant showed a similar pattern. The major difference was that the wormholes and plant roots were associated with the fissures between the pedons. Where structured heterogeneities such as cracks exist, their influence on solute transport is often increased by associated biologically formed pores which are disproportionately found in the less dense areas of the soils (Wang et al., 1986).

It is obvious from these studies that the "standard" homogeneous theory as used in current drainage design is not valid, especially if the soil is near saturation. To realistically predict the effect of drainage on shallow soils we need to consider the macropore domain. Macropores and fissures can only play an important role in the transport of water when the matric potential at the point of entry is close to zero (i.e. the soil is saturated). Once the macropores take part in water transport the conductivity will increase an order of magnitude. Barcelo and Nieber (1982), using a computer program, were able to simulate this conductivity increase. They found that when the soil is saturated, a pipe system increases the response to drainage, the peak discharge of the watershed, and the volume of water removed by the stormflow. Thus it is important to identify when and where the soil is saturated. This will be discussed in the next section which describes the process by which a shallow soil with a hard pan wets up during a rain storm.

WATER MOVEMENT

Hydraulic conductivity measurements for the topsoil on all three sites showed that the conductivity at the Willsboro site was the lowest (5 cm/hr) and at the Turkey Hill site the highest (in excess of 50 cm/hr). For all sites the infiltration capacity was in excess of rainfall intensity for almost all storms. Nevertheless surface runoff has been observed on many occasions at the Turkey Hill and Willsboro sites during only moderate precipitation events. Thus for all three sites the typical Hortonian assumptions that runoff only occurs when the infiltration capacity of the topsoil is exceeded by rainfall intensity is not valid. In these shallow soils there must be another mechanism for generating surface runoff.

Fig. 4 gives, for the Mount Pleasant site, the hydraulic potential, matric potential and pressure potential with depth for the row of tensiometers across the slope in the middle of the irrigated field. Line 1 shows the potentials in the morning after the previous day's irrigation treatment but before the present day's irrigation starts. The soil above the impermeable layer is unsaturated and the watertable is at some depth below the surface of the hardpan. Line 2 is the potential just before the outflow out of the drain starts (3.75 hours after the irrigation began).

The soil is unsaturated except for the hardpan surface, where the drain was located. Thus prior to drainage outflow, the water had moved downward as unsaturated flow. Only when the (unsaturated) wetting front reaches the hardpan surface does the watertable start building up. Tile outflow starts when the soil is just saturated. The watertable buildup continues until the losses through the fissures in the hardpan and the tile line equals the inflow. Line 3 represents this equilibrium situation during the precipitation event. The positive direction of the hydraulic potential gradient (Fig. 4b) clearly shows a downward movement of water into the hardpan. As the dye experiment later confirmed, this flow was through the wormholes and root channels associated with fissures. The next six lines represent the potential with depth on each following day. During the first two days there was a downward movement. Still, the potential at the hardpan surface decreased indicating that the fissures and cracks moved the excess water down the slope. At day 3 after rainfall the hydraulic potential gradient was zero indicating that the downward flow stopped. During the last three days there was a fast decrease in potential and an upward movement of water. For this soil the internal drainage in the profile was large enough that there was no surface runoff during the course of the experiment.

The Turkey Hill site, when compared with the Mount Pleasant site, had a top soil which had a higher permeability and a subsoil which was much less permeable. Fig. 5 shows the watertable height and the surface runoff (MacVicar, 1978). As soon as the watertable reached the surface overland flow began. Soon after the watertable dropped below the soil surface the runoff stopped, although there was some delay due to water moving down the hillslope. The piezometers which had an opening near the surface of the hardpan had the same level as the water on the surface of the soil, indicating that the hydraulic gradient was zero and no water moved into the hardpan. This interpretation was also affirmed by water balance studies (Steenhuis et al., (1984). There were no tension measurements made at the Turkey Hill site.

After the rain stops we expect to see a similar initial decrease in the hydraulic potential as was observed on Mount Pleasant. The matric potential at the hardpan surface will not decrease below zero as long as there is a positive hydraulic gradient. Water cannot move into the hardpan and has to move through the topsoil downhill. As long as the macropores are filled with water this process is relatively fast, but downward movement can be expected to quickly stop as soon as the matric potential at the surface becomes less than the depth of the hardpan. At this point the soil becomes unsaturated so the water can only move downhill under suction. This is a much slower process because the water cannot enter the macropores and tile lines under these conditions.

The rapid decrease in lateral flow at this cessation of macropore flow is indicated by the outflow hydrograph. Typical tile and surface outflow hydrographs for the Turkey Hill site are shown in Fig. 6. Notice that the tile line outflow is almost independent of the amount of surface runoff and rainfall as long as the soil is saturated. However, as soon as the rainfall stops, both the surface runoff and tile outflow decrease drastically. This is associated with draining of the macropores. Once the macropores are drained the tile outflow has been observed to trickle on for as long as five weeks when evaporation is small during the winter. During the precipitation and overland flow period, the tile outflow of 40 l/min was used to calculate an effective saturated hydraulic conductivity for the top soil. Depending on the assumption for hydraulic gradient near the tile, conduc-

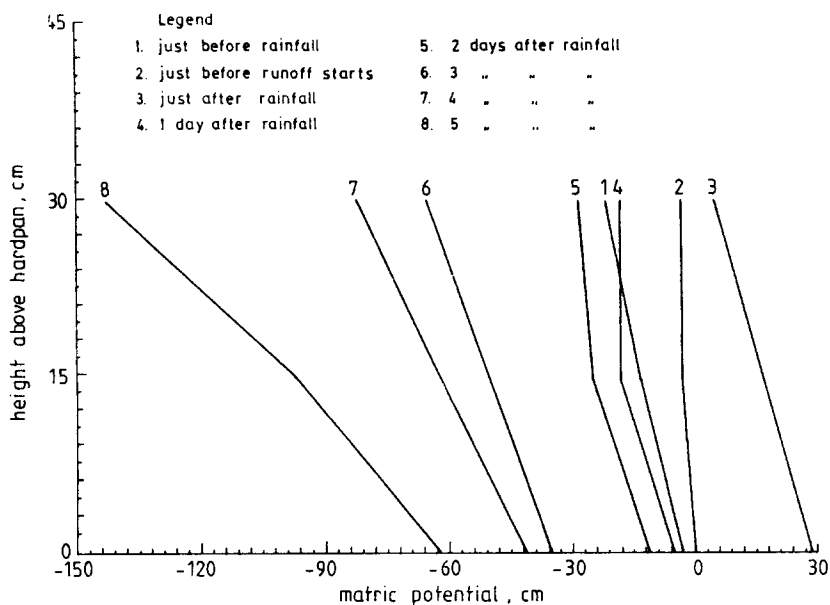


Fig. 4a. Matric potential for Mount Pleasant before, during and after artificial precipitation events.

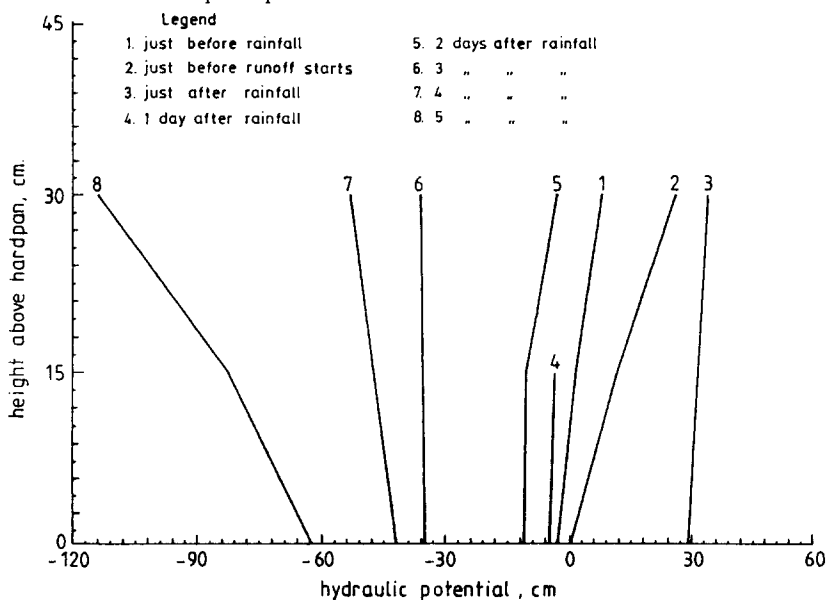


Fig. 4b. Hydrologic potential for the Mount Pleasant site before, during and after precipitation events.

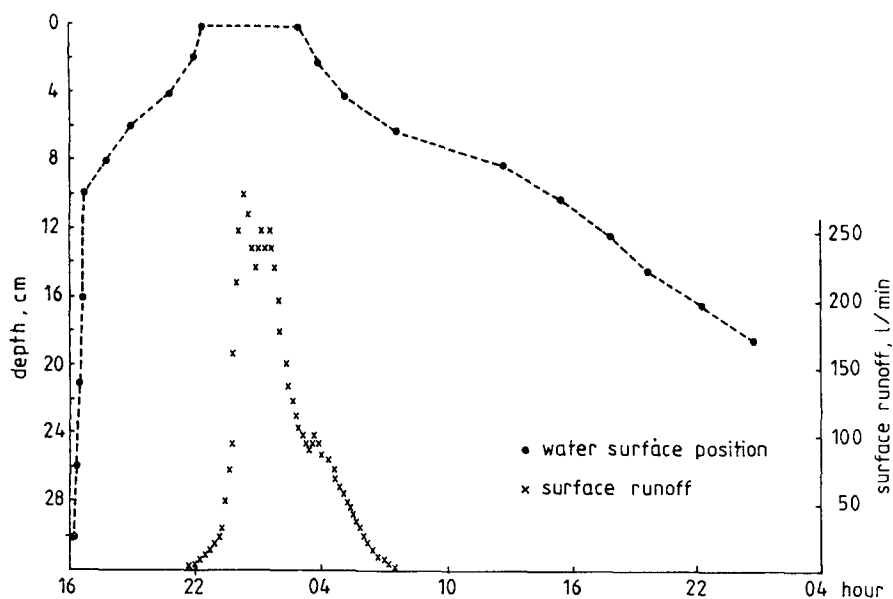


Fig. 5. Piezograph and surface runoff, 1600 September 24 to 0100 September 26, 1977.

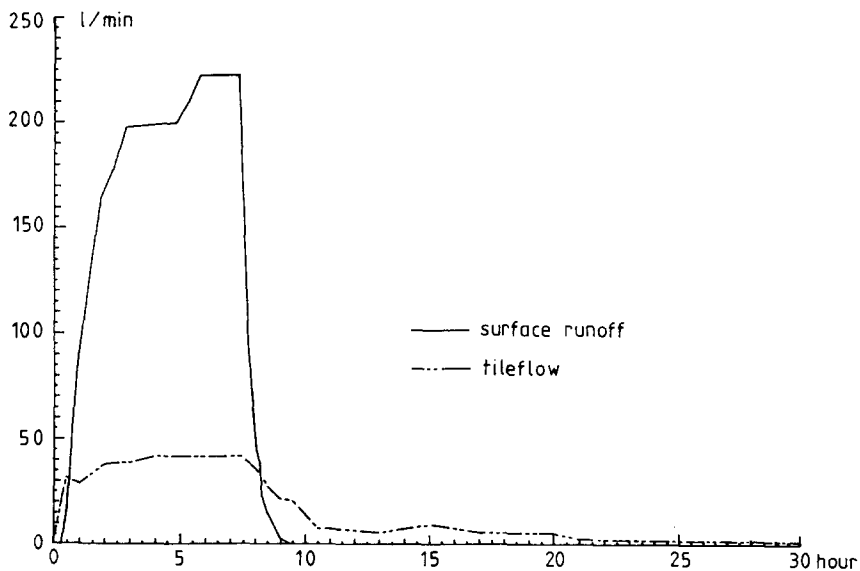


Fig. 6. Surface runoff and tile flow for a rainfall event with an intensity of 0.5 cm/hr. Rainfall started at $t=0$ hr and stopped at $t=9$ hr.

tivities of 10 m/day (unit hydraulica gradient) and 140 m/day (hydraulic gradient equal to the slope of the plot) (8%) were calculated. The value in the soil survey is 0.6 m/day. These high conductivities indicate the importance of the macropores in moving the water down the hill.

The results of the Willsboro site were different from the two other sites. This was caused by the layering of the soil, consisting of three distinct layers. The top 30 cm was relatively permeable; from 30 to 60 cm there was a dense hardpan, followed by a more permeable sublayer of sandy loam. In the nomenclature of Van Hoorn (1974) this is a typical heavy clay soil with the exception that while the matrix of the hardpan had an extremely low conductivity, water movement through this layer was aided by the worm and root channels. This was demonstrated by various dye experiments. The water movement in the hardpan layer was mainly vertical while horizontal movement towards the tile line was predominant in the saturated part of the lowest layer (Aburime, 1986). Unlike the Turkey Hill site where the water flowing down the slope can resurface at the bottom of the slope, the water in the bottom layer of the Willsboro site cannot resurface that easily because of the restricted hardpan layer overlying the more permeable layer. As we will see in the next section under these conditions installation of tile line is essential to drain off the excess water.

DRAINAGE, SLOPING SOILS AND HARDPAN CHARACTERISTICS

The previous section showed that preferential flow is often the most significant pathway for drainage on sloping soils. Evidence was presented which showed that the hardpans are not necessarily impermeable and in fact may transmit a large portion of the water. An earlier section indicated that drainage equations for sloping soils are based on homogeneous flow and impermeable hardpan in the true sense of the words, and often do not apply to actual field conditions. Consequently drainage equations for homogeneous soils are not applicable for shallow sloping soils with heterogeneous flow. In this paper we do not intend to develop new equations. However, we intend to show the implications of the previous experiments on drainage of these type of soils.

After a short review of both the homogeneous flow on sloping soils and nonhomogeneous flow on level soils, the importance of the flow characteristics of the hardpan on drainage will be shown.

Bouma, Van Hoorn and coworkers showed in various experiments the importance of cracks and preferential flow on carrying off water from the field to drains. However, these experiments were limited to level fields. To understand effects of preferential flow on trafficability on sloping soils with cracks two illustrative examples are presented. In these examples the matric potential at the surface, a proxy for trafficability, is compared with the depth to the (perched) watertable. When the matric potential is less than the depth to the saturated zone, then the hydraulic potential is positive and there is a net downward movement. Conversely when the matric potential at the soil surface is more than the depth to the saturated layer, water will move up and the watertable will drop. The soil becomes unsaturated when the watertable reaches the hardpan and evaporation is larger than precipitation. The following two hypothetical examples illustrate these points.

In the first example the hardpan has cracks a meter deep and a layer of

topsoil 30 cm thick, then the surface matric potential can decrease to -130 cm while the soil is still able to carry water off in saturated flow through the macropores at the bottom of the cracks. As trafficability is sometimes associated with a matric potential of -50 cm, this soil can therefore be trafficable soon after a heavy rainfall event. Drainage installed up the hill at some depth below the hardpan will intercept the cracks and be able to drain the macropores even faster. Consequently this soil can be drained very quickly to a moisture content that is trafficable.

However, consider the case where the soil has an impermeable layer which has no cracks. Assuming that the soil again has a 30 cm layer of soil above the hardpan then as soon as the surface matric potential decreases below -30 cm the water movement becomes much slower. This soil might not be trafficable for a considerably longer time, especially if evapotranspiration is small. As most of the soil is unsaturated tile lines will not take out any water except in isolated wet spots. This will only occur where the hydraulic conductivity and/or the hydraulic gradient changes, i.e. at the bottom of the hill. Thus, installing tile lines across the slope where there is no mechanism for initiating saturated flow, such as half way up the hillslope, will be of little help. The results found by Bornstein and coworkers underscore the importance of considering the unsaturated flow. Their experiments at the East Franklin site in Vermont included several drain tile spacings at various location across the slope. In this soil, which was a Cabot silt loam containing a tight hardpan, drain tiles did not significantly increase trafficability or accelerate drainage. Thus in their experiments, once the macropores in the topsoil drained, a fairly rapid occurrence under both drained and undrained treatments, water no longer could enter the drain tiles and they ceased to flow.

As we will see in the next section, older drainage practices have long taken advantage of these principles by concentrating the lines in naturally occurring wetspots. "Random" drainage, for example, takes advantage of naturally saturated areas to increase the tile flow.

A different situation exists at the Willsboro site. While the hardpan is permeable, the subsoil does not have a high enough conductivity or hydraulic gradient to rapidly carry the water off to the nearest stream. Subsurface drainage at regular intervals can therefore be extremely effective. The internal drainage of the Mount Pleasant site is good enough that no additional artificial drainage is required, although for less steep sites with lower hydraulic gradients drainage should make sense. In contrast, the conditions at Turkey Hill would prevent sustained tile flow and parallel drainage systems in such impermeable hardpans will be largely ineffective, as Bornstein and coworkers found.

One important conclusion of the forgoing analysis is that the subsoil is the most important factor in considering what kind of drainage system is required. The conductivity of the soil above the hardpan is of little consequence as long as there is a well developed macropore system, that can conduct the water to layers beneath. Drainage of shallow soils with a tight hardpan is a difficult task and it is not surprising to find that farmers keep these soils under a grass cover during the spring allowing the soil to dry up at a relatively fast rate due to the process of evapotranspiration.

IMPLICATIONS FOR DRAINAGE DESIGN

Despite many years of drainage research the drainage practices for shallow sloping soils are today practically the same as those described by Elliott in 1913 in his textbook "Engineering for Land Drainage". The three main systems of drains that are recommended by Elliot for these soils are the "natural" (now commonly referred to as "random"), the double main system and the Elkington (interception) system. Here are his descriptions:

"The Natural system consists of lines of tile laid in natural depressions that are wet and require draining more than the adjoining land. They are aids to natural drainage, and complete it in localities where the adjoining higher land is drained naturally by the low depressions. Such random or occasional lines are called upon to carry the drainage of both dry and wet land which is in fact often overlooked in apportioning the sizes of tile that should be used.

The double-main system is applicable to broad, flat sloughs, A main laid on each side of the slough as an intercepting line with laterals on the slope will be effective, if the drain is placed as deep as the stratum through which the water percolates.

The Elkington system was originated by Joseph Elkington of Warwickshire, England, in 1764. As now used, it consists of a few single lines of tile located as to intercept seepage water which percolates down a slope. In case the drain is not deep enough to fully intercept the water it is supplemented by wells which are made directly beneath the drain. These wells penetrate the strata from which the water proceeds and are made with an auger if the earth is firm clay, or are excavated and curbed with lumber or brick if the soil is loose or unstable. The office of such wells is to intercept the deeper currents of water. The pressure which forced the water through the soil causes water to rise in the wells and flow off through the drain which serves as an outlet to them".

Over the years countless drainage systems have been designed and installed based on these principles. That they remain a very viable alternative for drainage systems of shallow sloping soils is an indication that these drainage practices were based on sound physical principles. The many references to preferential flow ("deeper currents of water" is a good example) and the characteristics of the hardpan (i.e. "stratum through which the water percolates") are in excellent agreement with our findings: that the subsoil is the most important factor in considering what kind of drainage is required. It was also at the end of the previous century that Lawes et al. (1882) made the first observations on drainage on hillslopes. His observations clearly demonstrated the importance of macropores (or preferential flow) on the effectiveness of drainage characteristics.

More recently the importance of the crack system for drainage has also been found in the Netherlands. In extensive research to determine the most economical way of draining the Flevopolders in the old Zuiderzee, it was found that hydraulic conductivity was a poor predictor for the required drainage spacing. The best results were obtained when the cracking pattern was used as an indicator for the most optimal drainage spacing. The research of Bouma et al. (1981) confirms the importance of cracks in the subsoil.

While drainage systems have often been installed in a manner consistent with the concepts of preferential flow expressed in this paper, there has been little success to date in incorporating these concepts into theoretical formulations. The variety and variability of preferential flow phenomena challenge efforts to develop useful mathematical models of water movement in heterogeneous soil. In the interim, a greater emphasis on subsoil macropore hydrology will hopefully lead to more effective drainage designs.

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